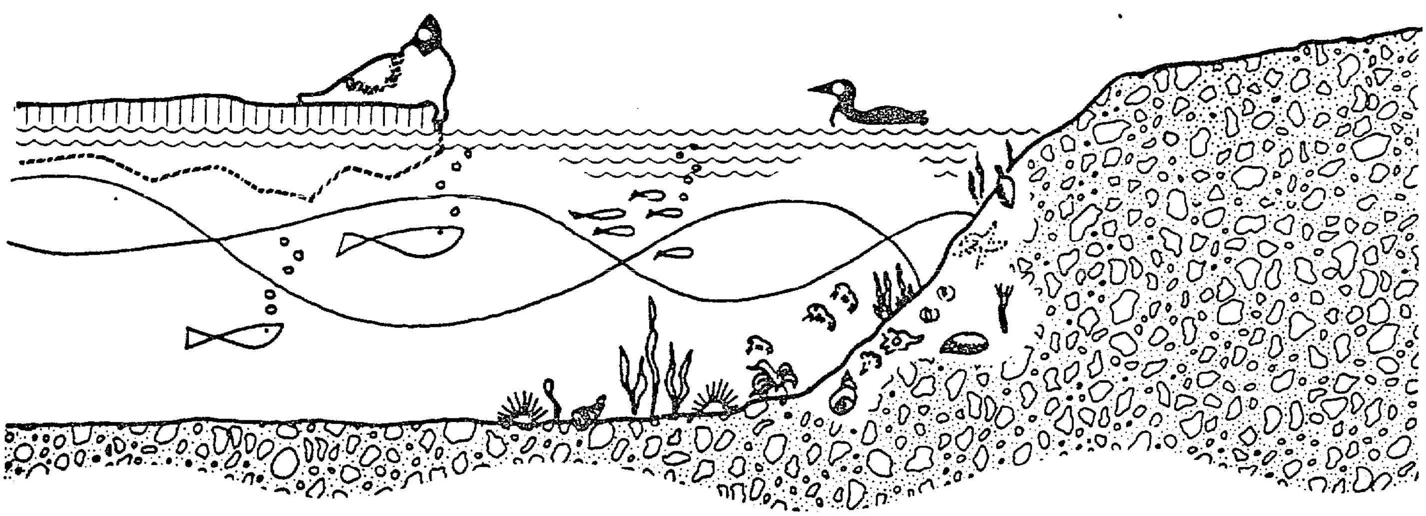
ICE CONDITIONS



Baffin Island Oil Spill Project

WORKING REPORT SERIES

BIOS
CAPE HATT

1981 STUDY RESULTS

BAFFIN ISLAND OIL SPILL PROJECT
CAPE HATT ICE CONDITIONS

for

Environment Canada
Environmental Protection Service
Edmonton, Alberta

12 March 1982

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ABSTRACT

Beginning in June 1981, five time lapse camera stations were operated on Cape Hatt to document ice break-up, summer movements, freeze-up and ice/ shoreline interaction processes. Films at Bays 9, 10 and 11 ran from June 1 to about July 10, then from late July to about August 10. A camera at Bay 11 continued on from 19-29 August, covering camp operations in the bay area. Tower cameras at Bay 11 operated from August 21 to September 21. Various camera malfunctions were encountered at Bays 102 and 103. Three films left running at the time of camp closure in September were not received in time for this report.

Direct field observations of ice break-up were not possible in this second year of the monitoring program, due to funding constraints. Observations were planned for the period of freeze-up but camp closed before the process began.

Spring break-up for the region was advanced by a week in 1981, with Arctic temperatures averaging above normal for the month of June, Ice formation at Cape Hatt occurred around October 19, two and a half weeks later than in 1980, and two weeks later than the historic normal. A pattern not recurring in 1981 was the drifting of multi-year ice floes down Navy Board Inlet to Cape Hatt, an event of September 1980. Based on observations of break-up and freeze-up in 1980 and 1981, Ragged Channel can be expected to have up to one week more open water than Eclipse Sound.

Summer open-water conditions at Cape Hatt were extended in 1981 by 27 days over 1980 and 17 days over the normal for the Cape Hatt/Eclipse Sound region. A total of 84 days of open water were evident at Cape Hatt from 1981 ice charts.

Studies of general ice conditions are not recommended for 1982. Recommended is the deployment of cameras to study particular areas of interest, such as the break-up and appearance of Bay n--the site of the neat oil spill, and in support of any ice mound study that may be conducted.

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1.0 INTRODUCTION AND OBJECTIVES

The B 10S ice monitoring program began in 1980 with the investigation of break-up and freeze-up patterns in the Cape Hatt area, the potential effects of ice, oil and sediment interaction, and ice /shoreline processes. The 1981 ice monitoring program was considerably reduced in both scope and level of effort from the 1980 study. The principle objectives at this stage were:

- to predict ice break-up at Cape Hatt in order to assist with the project scheduling during a critical project year

- to continue observations of basic break-up and freeze-up processes within the test bays with emphasis on the site of the neat oil spill

- to view the short term changes in beach appearance from oil discharge to freeze-up

Figure 1 shows the general location of Cape Hatt in the North Baffin Region.

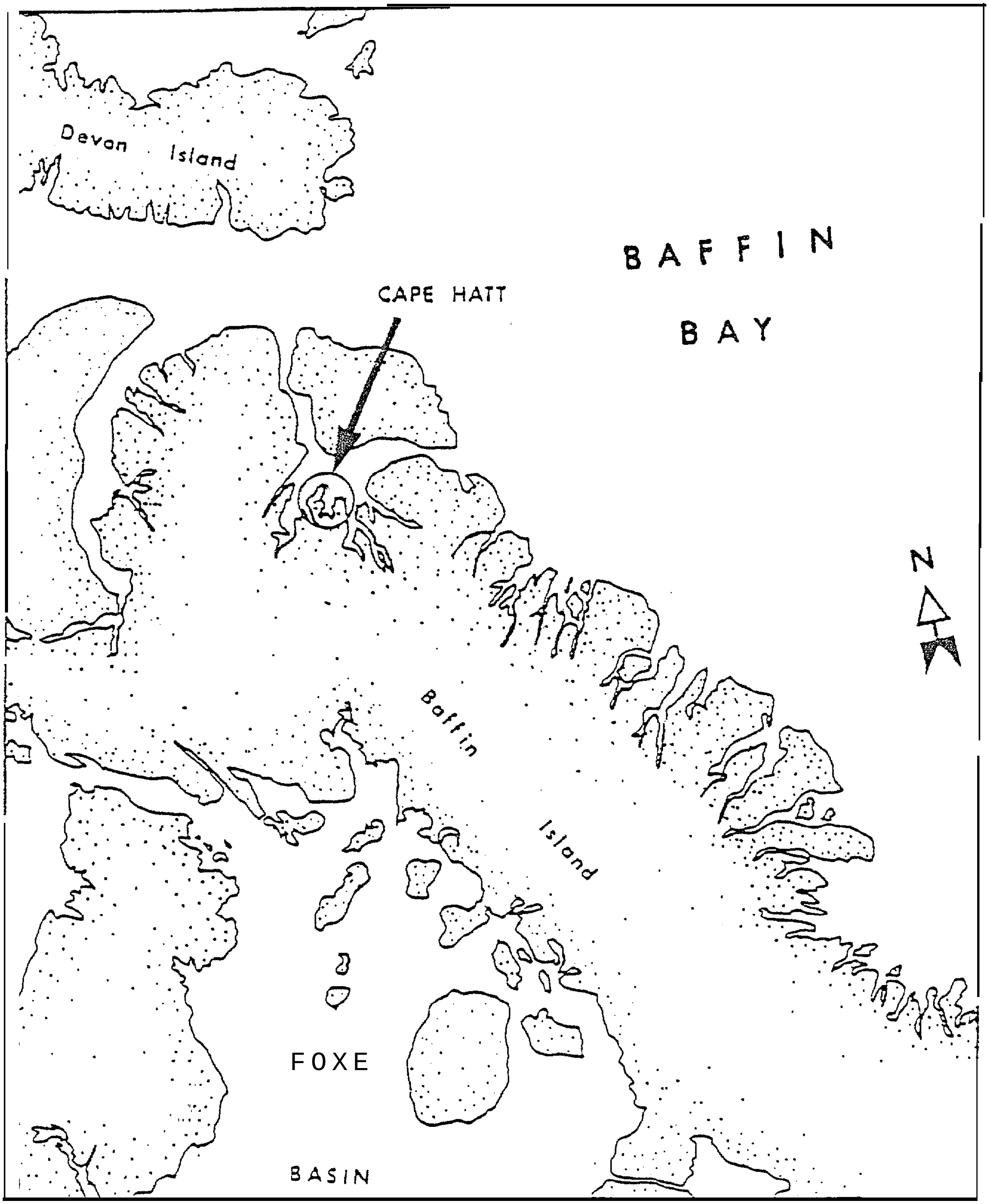


Figure 1 Location of Cape Hatt, Baffin Island

2.0 METHODOLOGY

Principal data sources for 1981 studies were:

Regional

1. A.E.S. Ice Charts
2. Landsat Imagery
3. Still Photography (J. Harper)

Shoreline

1. Time Lapse 8 mm
2. Still Photography (J. Harper)

Time Lapse camera stations were installed on 1 June 1981, with views of the beach face at Bays 9, 10 and 11. Cameras at Bays 102 and 103 malfunctioned, experiencing battery and light meter problems. The remaining three films ran until about July 10. The cameras ran again in Bays 9, 10 and 11 from late July to about August 10. Two cameras were mounted on a temporary tower to view the appearance of the oiled intertidal zone in Bay 11 between August 21 and September 21 (see Plate 1). Figure 2 shows areas of coverage of the individual stations. Table 1 outlines intended and actual film operation times and summarizes ice conditions for each camera station. Note that films left running after camp shutdown in September 1981 were not available at the time this report was written.

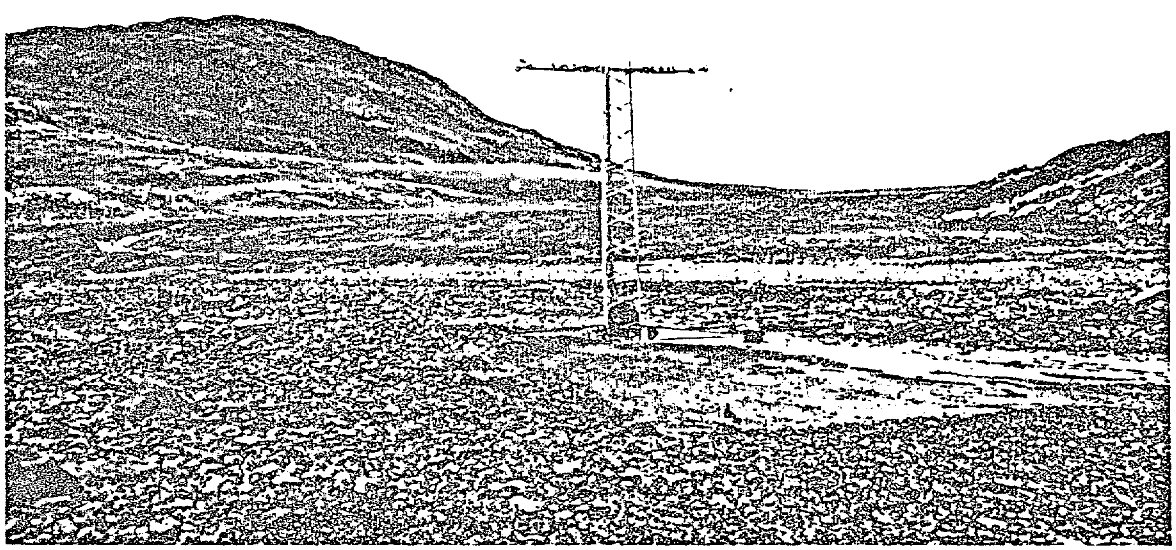


Plate 1 Time Lapse Camera Tower, Bay 11

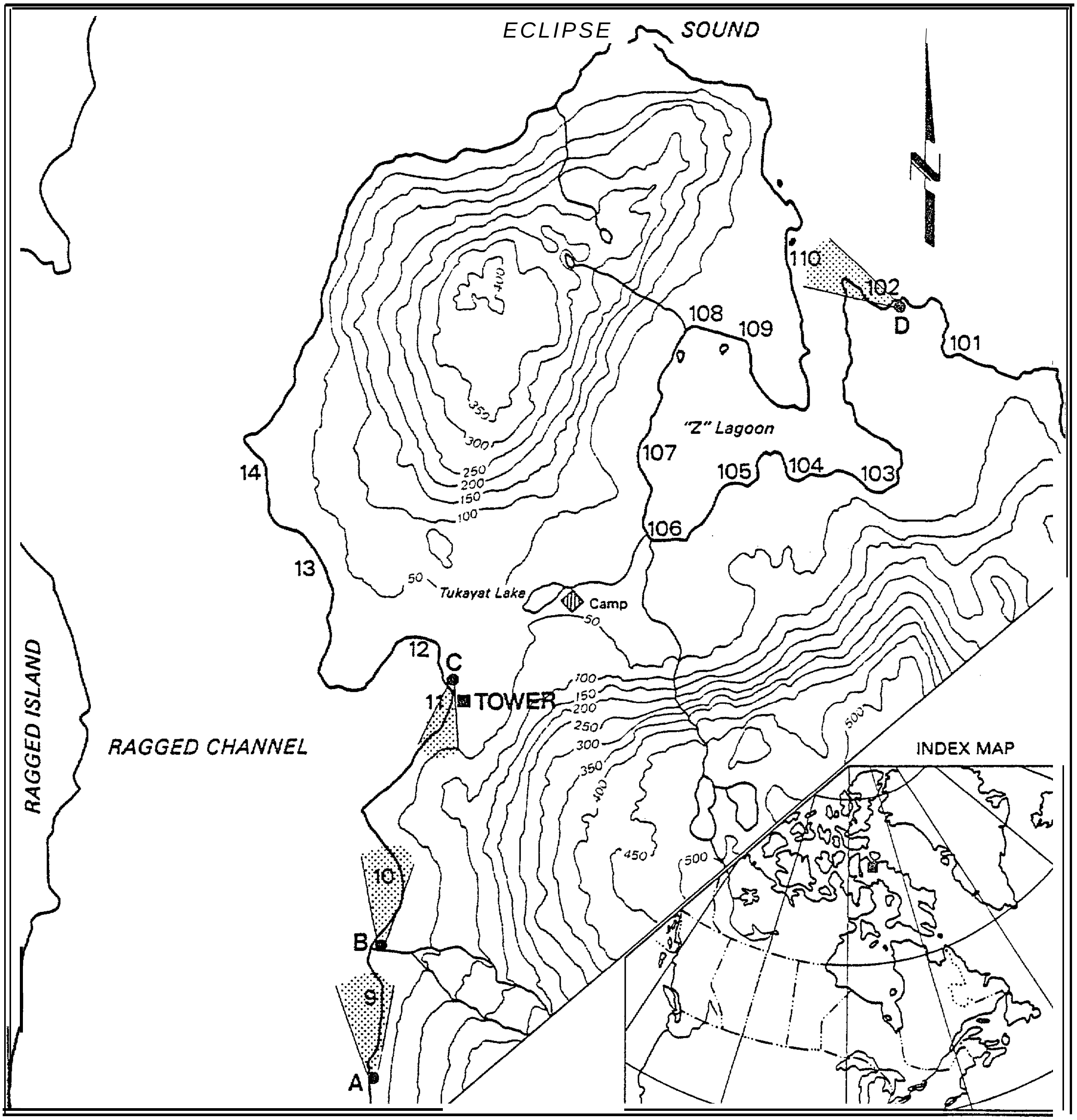


Figure 2 Camera Locations on Cape Hatt, June to September 1981

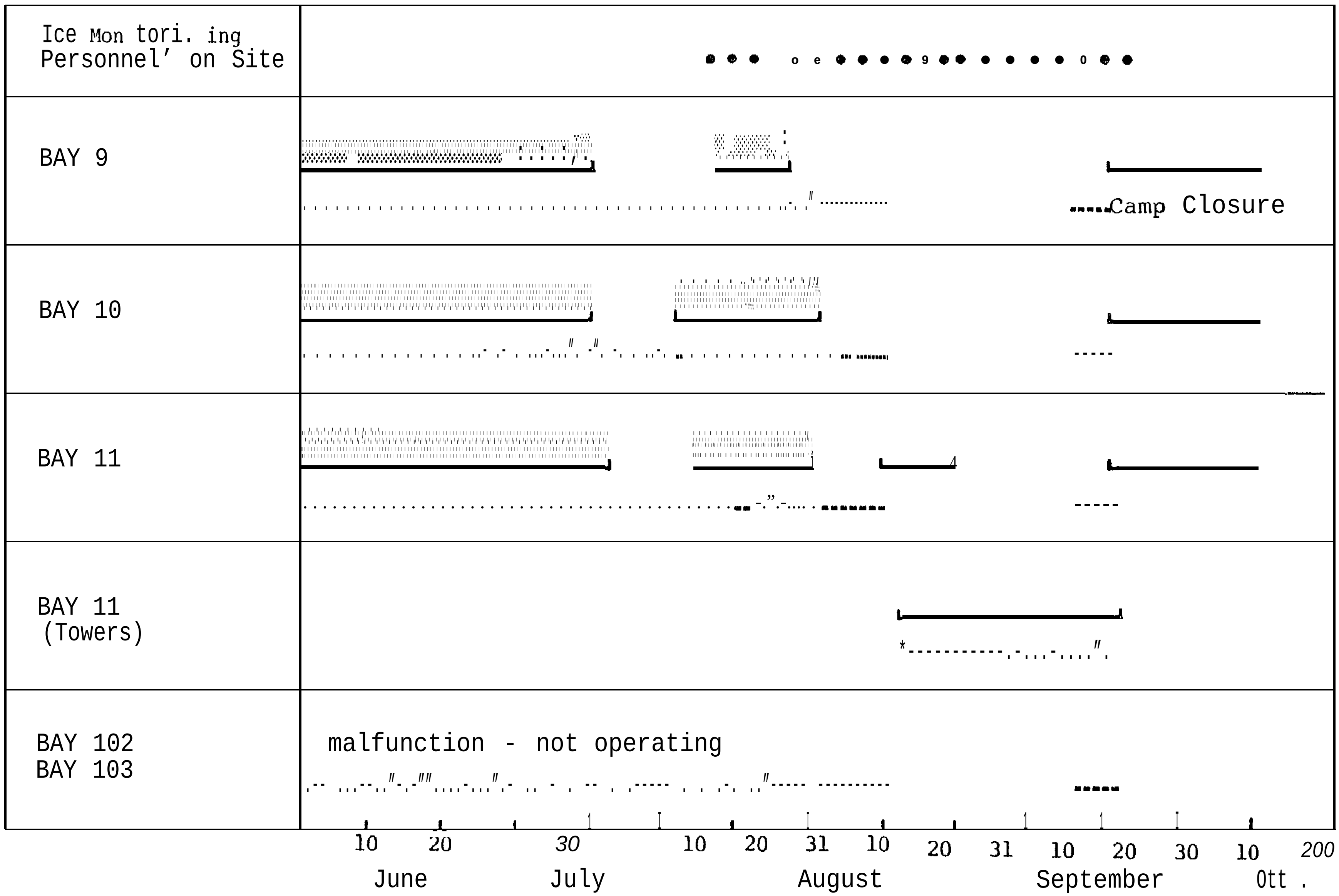


Table 1 Time Lapse Film Coverage and Ice Condition Summary 1981

------Intended Operation Period — Actual Operation Period and Ice Conditions

Solid Ice Cover Broken Ice Floes

In total, over 180 camera days of good quality time lapse footage was obtained in 1981. Interruptions in coverage due to lens fogging averaged less than 10%. Ragged Channel break-up was missed by a two week break in film coverage, but notes taken by microbiologists together with ice charts, provide a good indication of break-up. Successive Super 8 movie films have been spliced into 100-200 foot reels for each station, and reviewed according to ice conditions and ice movement on a daily basis.

Only one Landsat image was useful of the Cape Hatt/Eclipse Sound Region in 1981 showing either break-up or freeze-up conditions. A Landsat image from 13 July shows initial major fracturing of ice and ice melting at shore edges (Plate 1).

Ice thickness and snow depth records for Pond Inlet were updated from A .E. S. statistics for winter 1981. The period between winter 1977 and 1981 is still lacking data. Temperature records for Pond Inlet, virtually representative of Cape Hatt (±2° C) are included in Figure 4 for May through October 1981.

The prediction methodology involved:

1. Interpreting 1980/81 winter conditions from air temperature, snow-fall and ice thickness departure from normal.

2. Utilizing predicted climate trends and A .E .S. ice synopsis for Pond Inlet.

3.0 REGIONAL ICE CONDITIONS

3.1 Historical

The Cape Hatt/Eclipse Sound region is linked each winter by a continuous sheet of shore fast ice, as shown in Plate 1. The mean June ice thickness at Pond Inlet is 157 cm (Allen 1977). Ice and snow thickness summary statistics for Pond Inlet are presented in Table 2 and Figure 3. First melting occurs in late June or early July along shorelines. Open water spreads west to Eclipse Sound by late July. With final break-up, remaining ice drifts south into the west end of Eclipse Sound.

Table 3 summarizes 18 years of break-up and freeze-up dates for Cape Hatt. Derived from this are the open water periods for Cape Hatt (Table 4) reaching a maximum of 91 days in 1973, and a minimum of 35 days (questionable) in 1972. The open water period averages 63 days from late July, early August to late September, early October.

Based on ice charts and Landsat imagery, regional ice conditions at the Cape Hatt site (Ragged Channel) can be summarized as follows:

Table 5 Summary of Regional Ice Conditions

	1981	1980	Mean	Earliest	Latest
Clear of Ice <2/10	July 28	July 27	July 31	July 15 (1958)	August 20 (1972)
Freeze-Up	Ott 19	Sept 30	Ott 6	Sept 24	October 19 (1981)

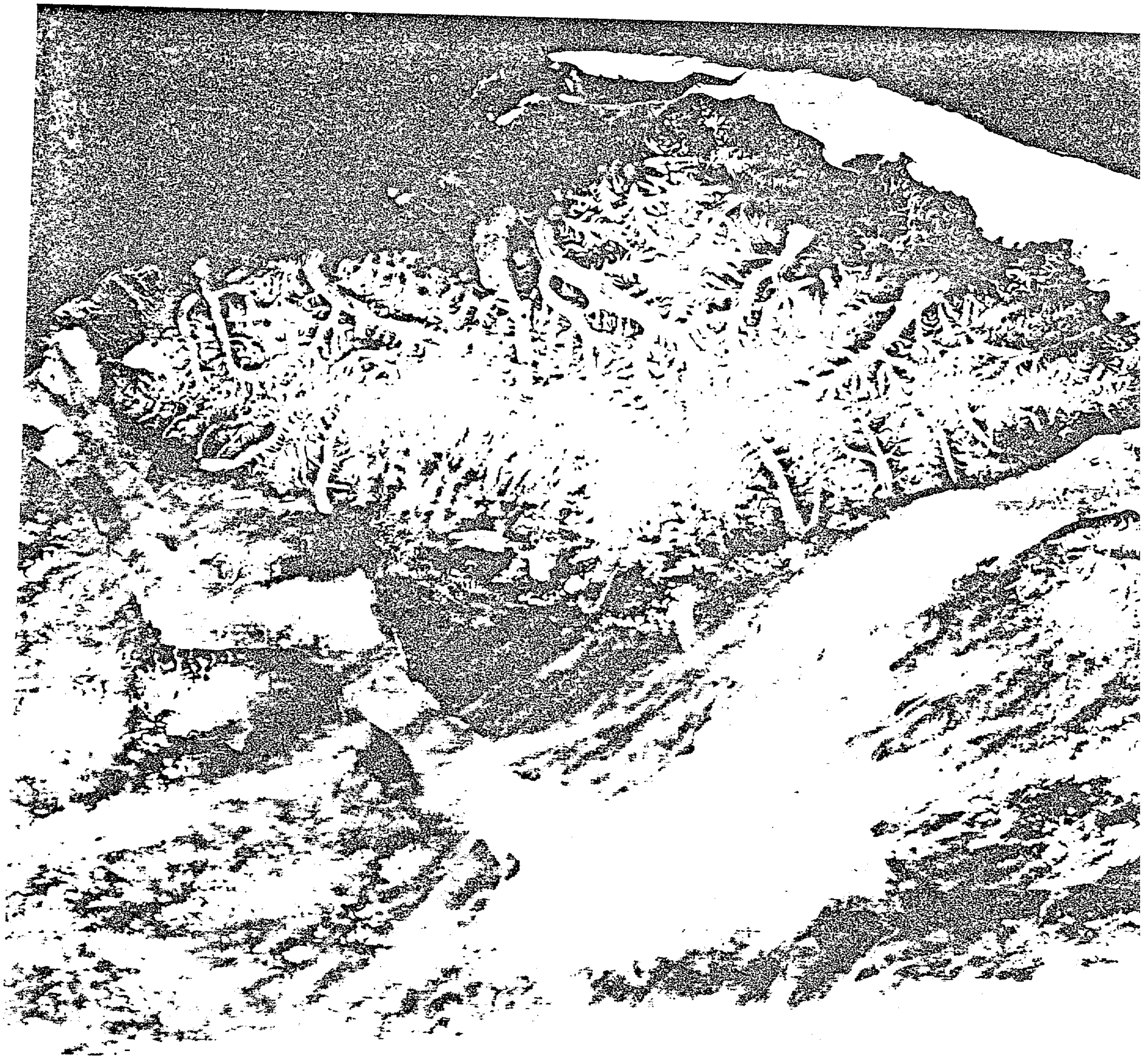


Plate 2 Landsat Image of 13 July 1981 showing first fracturing of ice and open water areas along shore in Eclipse Sound, Cape Hatt region. Open water to the North in Lancaster Sound.

Table 2 Historical Ice and S now Thickness, Pond InJet

Year	Maximum Ice Thickness (cm)	Date First Ablation	Max. Snow Depth (cm)
1964/65	147	June 23	15
1967/68	142	June 15	25
1969/70	116**	N/A	28
1974/75	178	N/A	12
1975/76	195	N/A	15
1976/77	N/A	N/A	22
1977/78	157	June 10	12
1980/81	134	N/A	14

First Permanent New Ice: 30Nov 1975, 22 Oct 1976, 21 Ott 1977
First Ice Deterioration: 18 June 1976, 15 June 1977, 17 June 1978

**Note: S .S. Manhattan reported ice thickness values between 137 and 183 cm at eastern entrance to Pond Inlet, May 11-15, 1970. OnMay16, Manhattan ice observers reported 122 cm of ice, 10 miles WNW of the village, in Eclipse Sound. Snow depth at the time was 43 cm (Billelo, 1972).

1970 was a year with ice thickness much less than normal. This was reflected in a break-up starting July 16, up to 2 weeks ahead of the mean (Table 2).

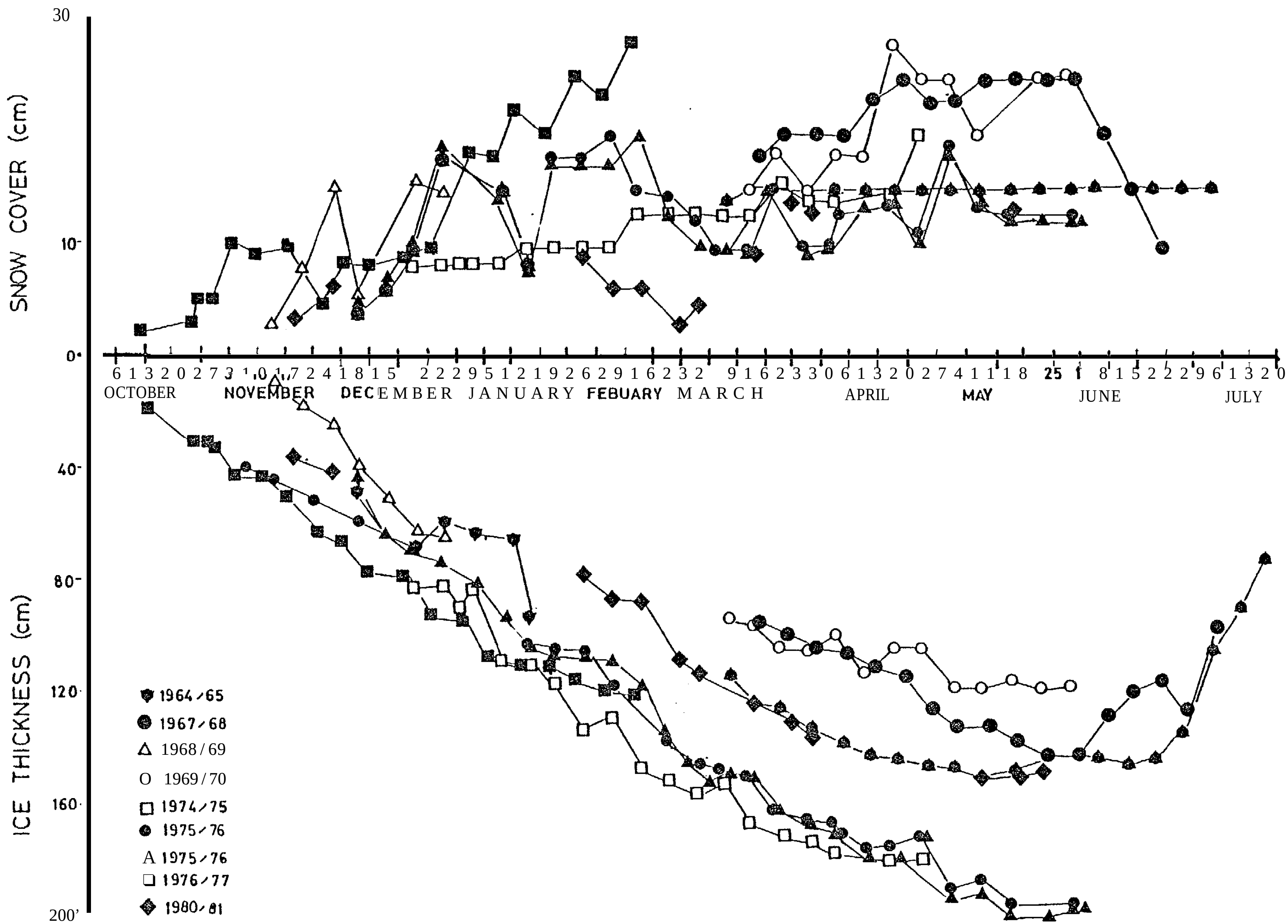


Figure 3 Historical Ice and Snow Thickness Pond Inlet

Table 3 Break-Up and Freeze-Up Summary
Cape Hatt 1964-1981 (Ice Charts)

Year	Break-Up Date	Freeze-Up Date
1964	23 July - 30 July	24 September - 08 October
1965	23 July - 30 July	24 September
1966	23 July - 30 July	15 October
1967	10 August	24 September - 08 October
1968	03 August	10 October - 15 October
1969	03 August	24 September - 08 October
1970	16 July - 23 July	08 October - 20 October
1971	23 July	08 October - 20 October
1972	20 August**	24 September
1973	23 July	22 October - 29 October
1974	9 July - 13 August	15 October
1975	23 July	24 September - 08 October
1976	21 July - 01 September	06 October - 27 October
1977	27 July - 03 August	12 October - 26 October
1978	01 August	19 September - 03 October
1979	31 July - 07 August	09 October - 23 October
1980	30 July - 05 August	01 October - 05 October
1981	21 July - 28 July	20 October - 27 October

Note: The range of dates indicates the approximate time span (where known) between first significant fracturing and concentration less than 2/10 and first new ice and a stable cover.

Note: Break-up is a function of maximum ice thickness (dependent largely on snow cover and freezing degree days) and June, July thawing air temperature and solar radiation.

**This date is in doubt.

Table 4 Open Water Period, Cape Hatt 1964-1981
(Ice Charts)

Year	Days Open Water	Open Water Period
1964	56	30 July - 23 September
1965	56	30 July - 23 September
1966	77	30 July - 14 October
1967	45	10 August - 23 September
1968	68	03 August - 09 October
1969	52	03 August - 23 September
1970	77	23 July - 07 October
1971	77	23 July - 07 October
1972	35**	20 August - 23 September
1973	91	23 July - 21 October
1974	64	13 August - 15 October
1975	64	23 July - 23 September
1976	46	01 September - 05 October
1977	70	03 August - 11 October
1978	49	01 August - 18 September
1979	63	07 August - 08 October
1980	57	05 August - 30 September
1981	84	28 July - 19 October
Mean	63 days	

**This is in doubt.

(Derived from Table 3 "Break-Up and Freeze-Up Summary, Cape Hatt 1964-1981")

3.2 1981 Ice Conditions

Predictions

The winter of 1980-81 was characterized by above normal temperatures in November, January and February, normal from March to April. May temperatures were slightly below normal, First thawing degree days started to accumulate about June 8 compared to June 15 in 1980. Temperatures for the remainder of the melt period in 1981 were similar to the previous summer with the exception of an unusually warm period from July 10-20 (Figure 4).

In arriving at a break-up prediction in June 1981, the temperature patternswere.combined with other evidence showing an above normal snowfall for the 1980/ 81 winter and ice thickness . in the N. Baffin region about 25 cm below normal. On June 16, A.E. S. advanced their Pond Inlet first fracturing date from July 15-20 to July 8-13. In 1980 Ragged Channel break-up commenced about 5 days after Pond Inlet fracturing. On this basis Ragged Channel break-up was predicted in mid-June to occur between July 13 and 18. Actual field observations by the microbiologists indicated a badly broken ice cover in Ragged Channel by July 15 deteriorating to small loose floes by July 17. Between July 21 and 29, deteriorating ice freely moved back and forth within the channel.

Actual Regional Conditions

1981 ice conditions at Cape Hatt were characterized by early beak-up and record late freeze-up, with an open water period of 84 days--the longest in 9 years (Figure 5). The early break-up was aided by above normal temperatures for the Arctic in June. A later freeze-up may be partially attributed to the fact that no multi-year ice floes drifted south down Navy Board Inlet directly to the Cape Hatt region, as occurred in September 1980. Following ice charts document break-up and freeze-up at Cape Hatt in 1980 and 1981 (Figures 6 and 7).

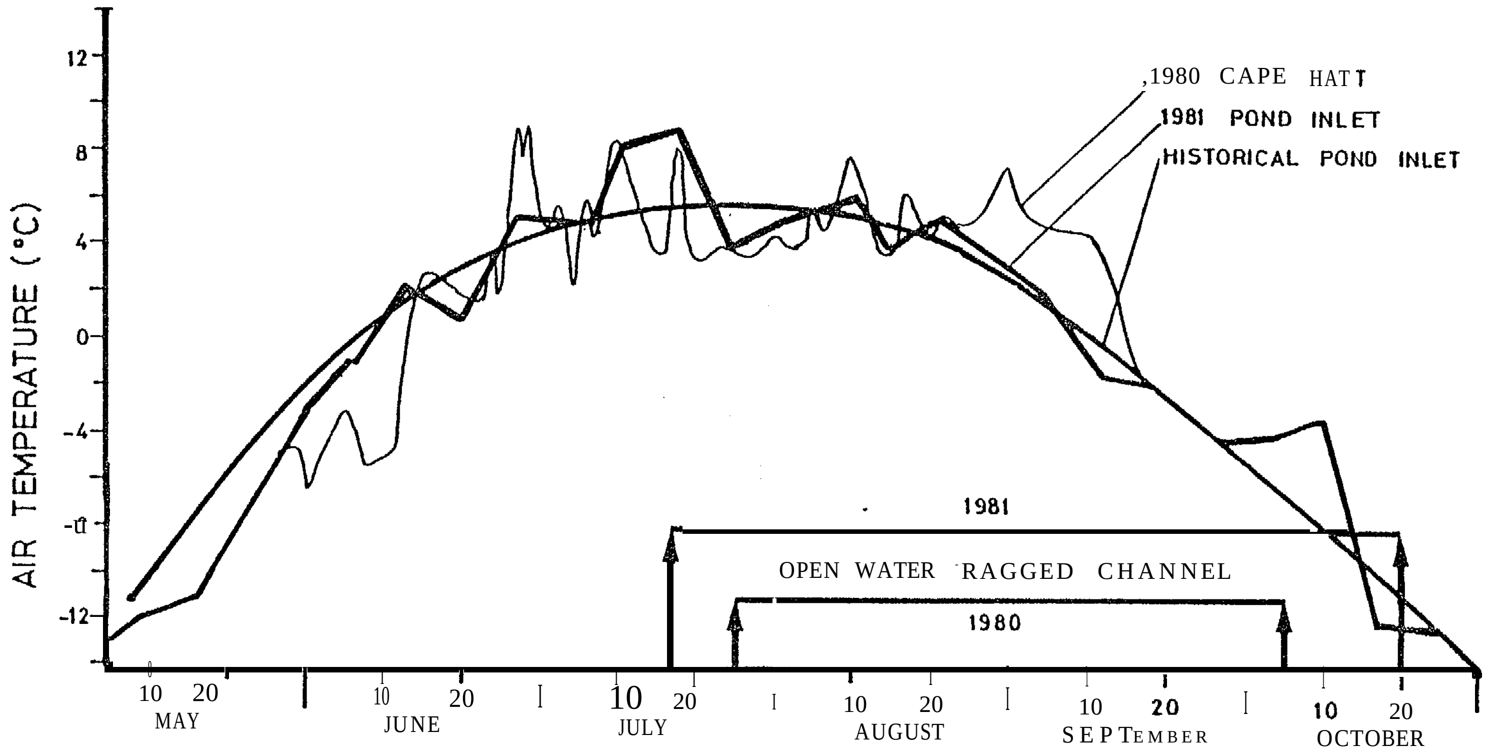


Figure 4 AVERAGE TEMPERATURES CAPE HATT AND POND INLET

POND INLET	NORM	1979	1980	1981
1st Ice Fracture	28/7	4/8	25/7	13/7
1st Clear	1/8		5/8	28/7
1st New Ice	6/10		30/9	13/10

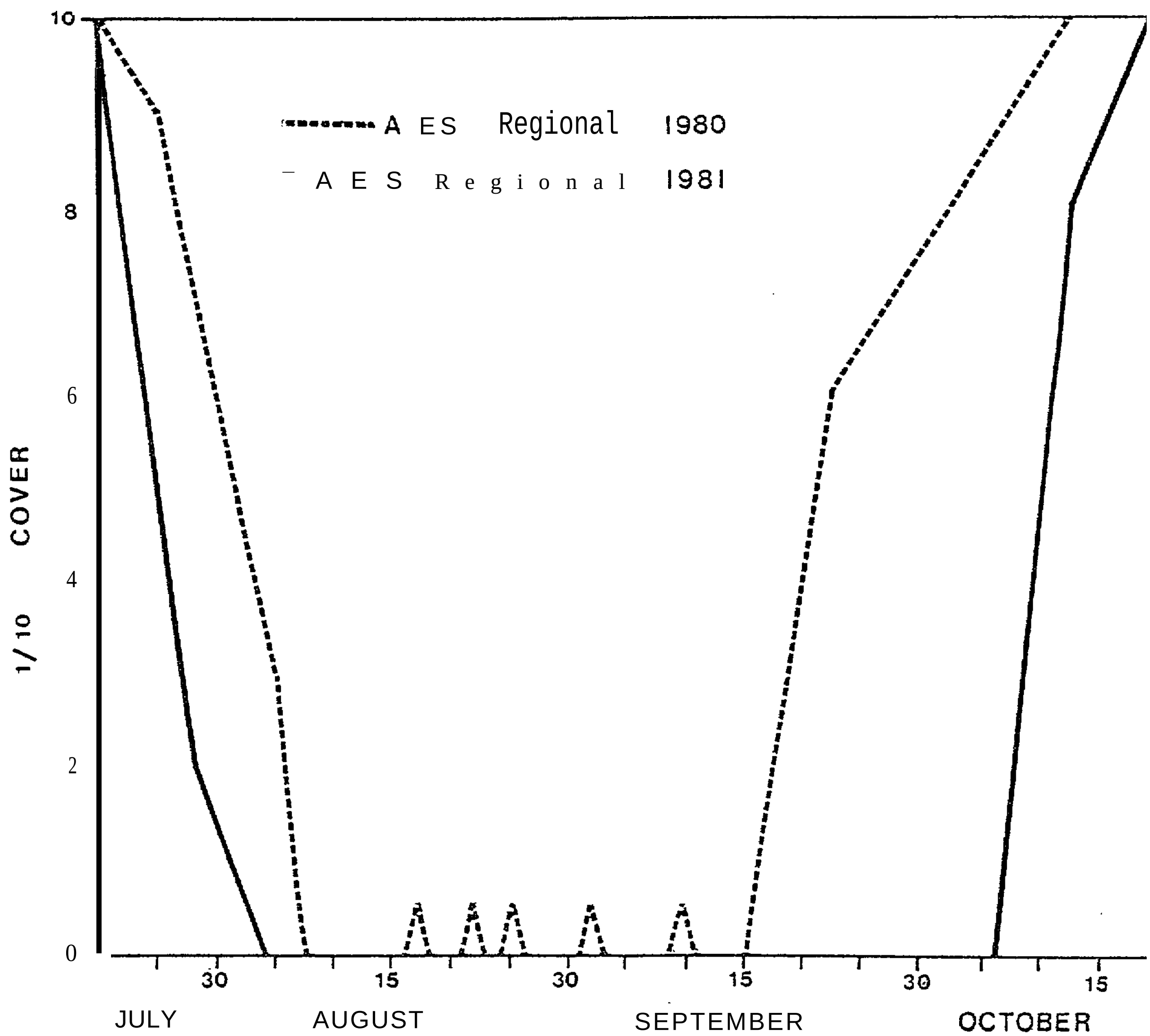
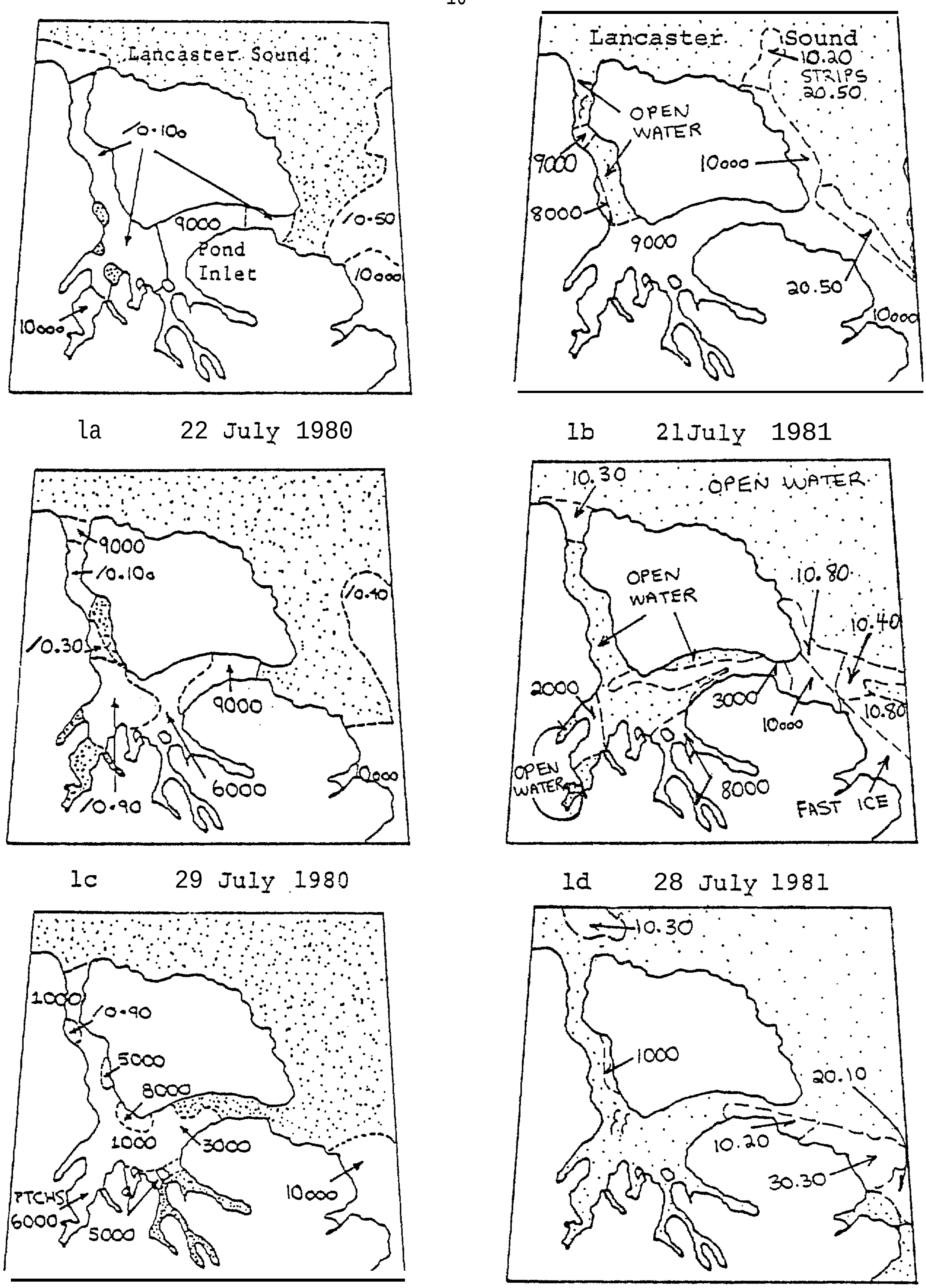


Figure 5 Ice Conditions, Cape Hatt 1980 and 1981



1a 22 July 1980

1b 21July 1981

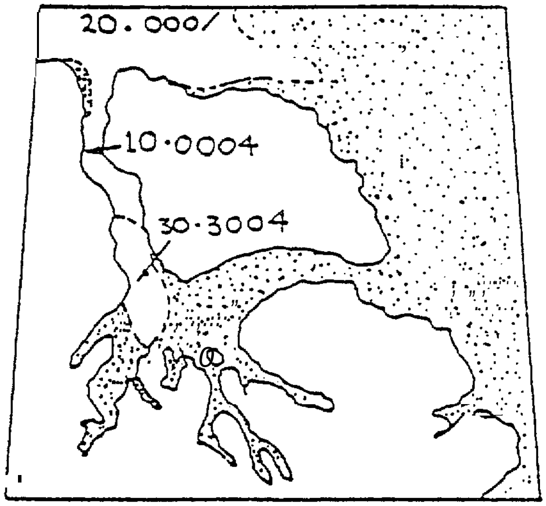
1c 29 July 1980

1d 28 July 1981

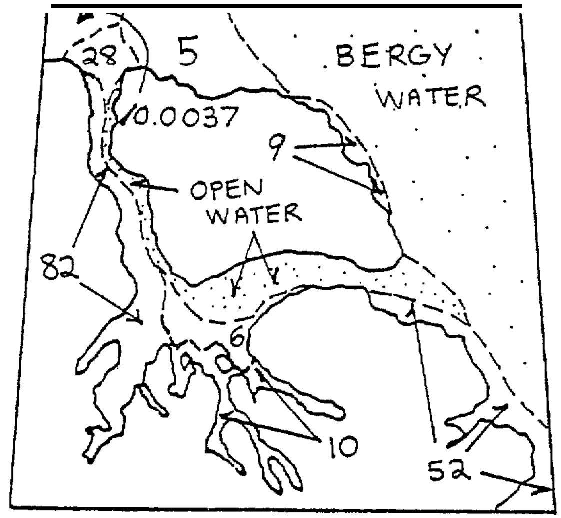
1e 5 August 1980

1f 4 August 1981

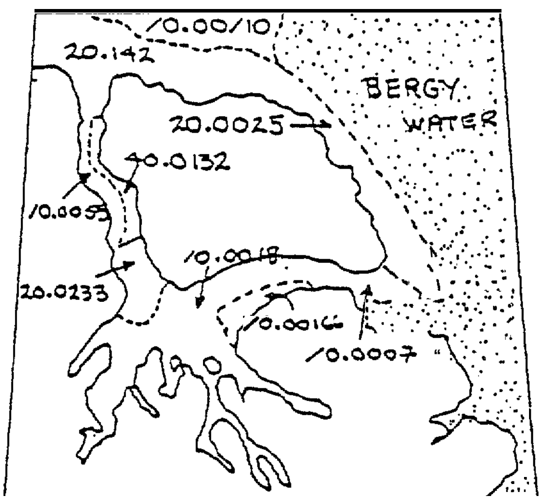
Figure 6 Ice Charts, Break-Up at Cape Hatt 1980 and 1981



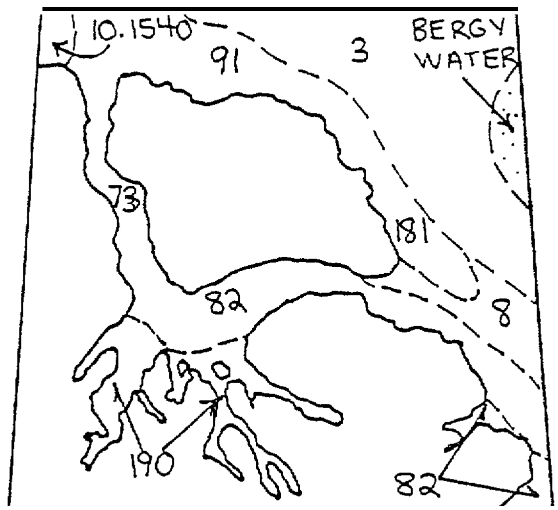
2a 23 September 1980



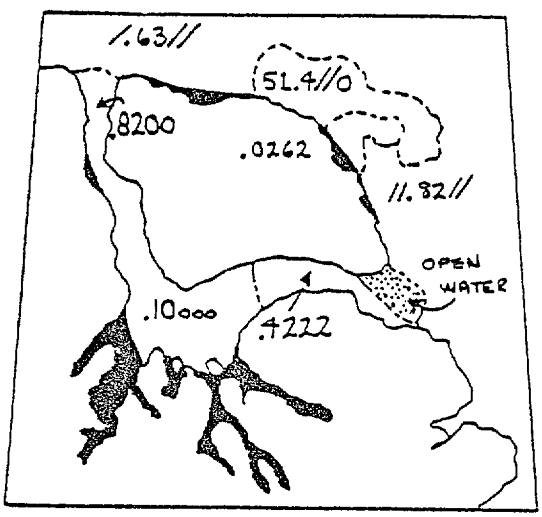
2b 20 October 1981



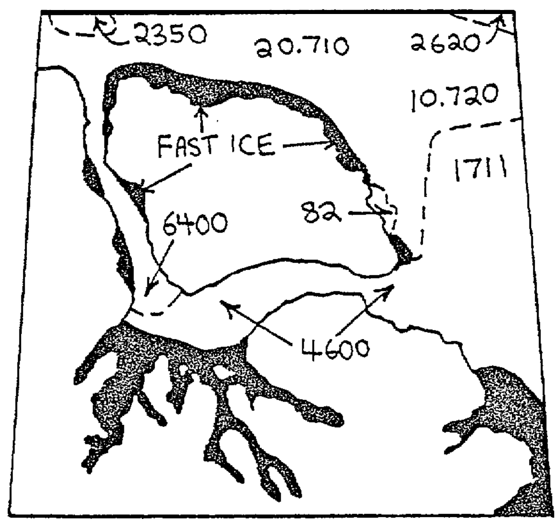
2C 7 October 1980



2d 27 October 1981



2e 11 November 1980



2f 10 November 1981

Figure 7 Ice Charts, Freeze-Up at Cape Hatt 1980 and 1981

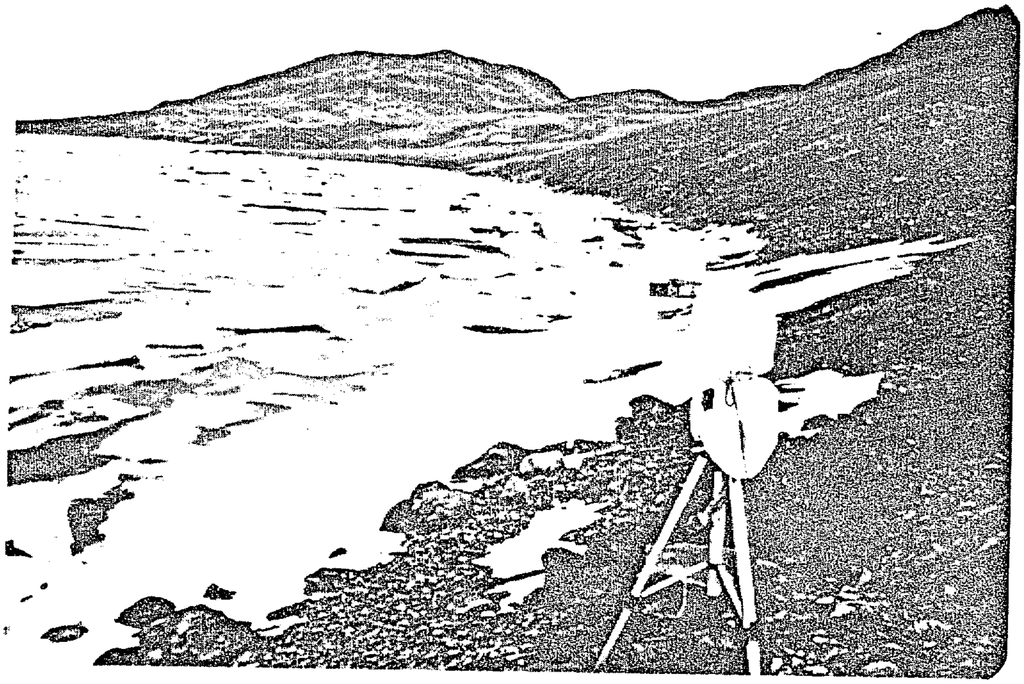


Plate 3 Bay 9, 27 July 1980

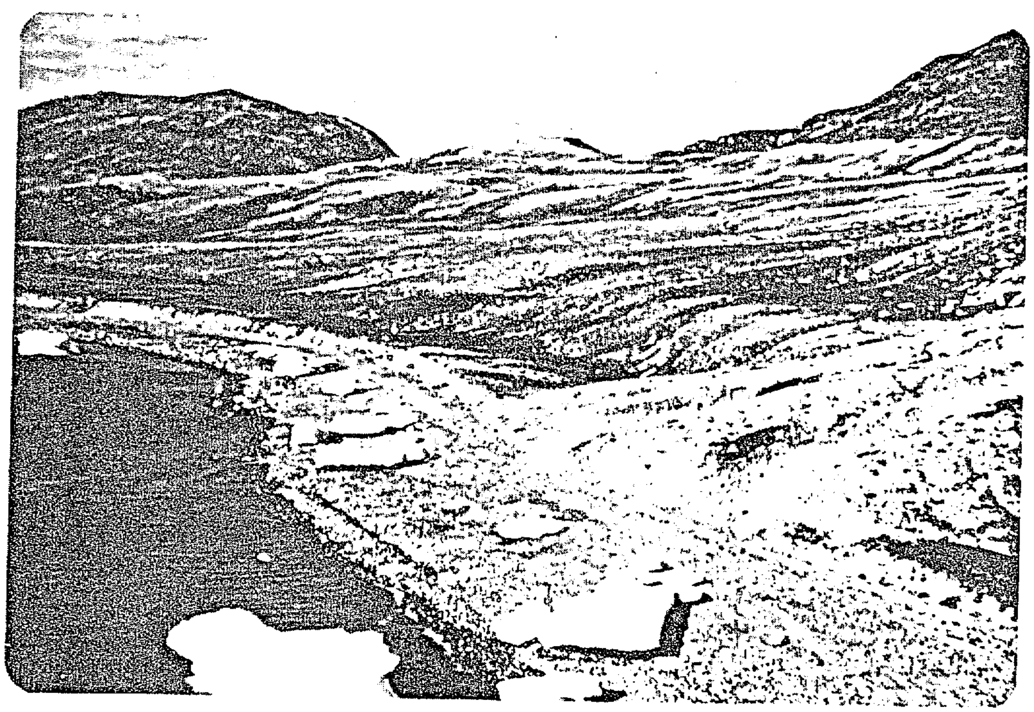


Plate 4 Bay 9, 29 July 1981

Initial weakening of the ice cover was noted from the Landsat image of 13 July 1981 (Plate 2). Major fractures were evident in Pond Inlet and Navy Board Inlet (Cape Hatt is largely obscured by clouds). Open water areas were found predominantly along the west shoreline of Navy Board Inlet. A similar pattern in stages of early break-up exists in the historical record and for 1980.

By 21 July 1981, stretches of open water in Navy Board Inlet reached as far south as Eclipse Sound and Ragged Channel was in an advanced state of break-up. In 1980 Pond Inlet was the first to clear, following the historical pattern. By 22 July 1980 the only patches of open water were northwest of Ragged Island.

Cape Hatt was in completely open water by 28 July 1981, about one week earlier than in 1980. Ice cover was 4/10 at the north entrance to Navy Board Inlet, and 3/10 at Pond Inlet. The historical trend was follow ed with remaining ice drifting to the west end of Eclipse Sound. Contrasting ice coverage at Bay 9 between 1980 and 1981 is visible in Plates 2 and 3, although through films at the site, there are more ice floes in Bay 9 in 1981 than are indicated from the photo alone. Table 3 shows the period of open water at Cape Hatt for 1981 as 84 days, compared to 57 days in 1980 and an historical average of 63 days.

A record late freeze-up was experienced in the Cape Hatt region in 1981. The area remained clear of ice until around 20 October, when the bays to the south and the west half of Navy Board Inlet were covered with new and grey ice. Open water was still found in the east end of Eclipse Sound. Ice cover of 10/10 was reached by 27 October 1981 in Eclipse Sound, Navy Board Inlet and the bays to the south of Cape Hatt. Complete 10/ 10 ice cover was formed by approximately the same time in 1980, however 9/10 ice rover was reached three weeks earlier in 1980.

4.0 ICE INTERACTION WITH THE SHORELINE

Earl y film coverage of Bays 9 and 10 from June 1 to July 10, 1981 showed a predominantly solid ice cover, with the ebb and flow of the tides breaking the floating ice surface into floe shapes and forming zones of rough ice in the intertidal zone. The shorelines were from one-half to totally covered with ice and snow. The tidal crack between bottom fast ice and floating ice was distinct in Bays 9 and 10, following shoreline contours. Ridging effects were visible on either side of the tidal crack in Bays 9 and 10. Stormy weather appeared to coincide with higher water levels and accentuated ridging and ice breakage. Rise and fall of water levels with the tide was much less apparent on the films for Bay 11 (shallower bottom slope). The floating ice surface was interrupted by apparently random rough ice features, most likely older ice floes left from freeze-up the previous fall.

Open water areas began to develop in Bays 9 and 11 in early July. Snow and ice melt occurred on the beach face at Bay 9, while 'ice clearing was taking place seaward of the tidal crack. Ice floes stranded on the edge of the beach face in Bay 9 had a sediment layer on top. This was the only clear evidence in film coverage for 1981 of the process of sea ice transfer of beach mat erial, observed in more detail the previous summer (see 1980 report - Cape Hatt Ice Conditions).

Open water conditions progressed in a different manner in Bay 11. Ice floe circulation was not as active as in Bay 9, but open water developed rather as a result of flooding at the edges of lifted ice floes and over the landfast ice.

Final stages of break-up were filmed from late July to about August 10. S bores were generally free of ice and snow, and broken ice floes circulated within the bays. High tide lifted and deposited ice floes onto the beach face and in Bay 11, to the high tide level. Successive tides moved the floes further along the beach or out into the bay. Circulation patterns in the bays are not certain in a brief overview of the film coverage, but ice movement was thought to generally follow a clockwise movement in Bay 9, and counterclockwise in Bays 10 and 11. Complete circulation of ice floes was much less apparent in Bay 11.

An overview examination of beach topography revealed raised linear features in the intertidal zone of beach gravels in all Bays. Linearity was most evident at Bay 9, with coincidental features paralleling the shoreline. High tide reached upward just to the point of contact with the seaward ridge. These berms were more hummocky in character in Bays 10 and 11, with evidence of meltwater from the backshore perhaps eroding the berms from behind and at several points breaking through. These potential ice mound features, evident in all Bays, appear to be of the same character as those photographed in 1980, and studied in field excavations in May 1981 (Sempels 1982).

5.0 CONCLUSIONS

Film coverage of Bays 9, 10 and 11 documented ice/shoreline interaction processes from June 1 to about August 10. Zones of rough ice and tidal cracks were identified as well as the development of open water areas. Ice clearing took place seaward of the tidal crack in Bay 9, while in Bay 10 flooding over the landfast ice occurred. High tides left ice floes stranded on the beach face, and at the high tide level in Bay 11. Evidence of sea ice transfer of beach material was present in a sediment layer on top of ice floes in Bay 9. Raised linear features, potentially ice mounds, were noted in the intertidal zone of beach gravels in Bays 9, 10 and 11.

Break-up at Cape Hatt in 1981 began about July 21, a week earlier than in 1980, aided by above normal temperatures for the Arctic in June. At that time, stretches of open water extended from Navy Board Inlet to Eclipse Sound. Ragged Channel was in an advanced state of break-up. Although about 10 days earlier than normal, the general pattern of initial ice fracturing near Pond Inlet proceeding to open water areas along the shoreline of Navy Board Inlet, followed the historical pattern. .

The 84 day open water period in 1981 was the longest in 9 years. Cape Hatt was in completely open water by 28 July 1981, about one week earlier than in 1980. A record late freeze-up occurred in 1981 with the area remaining clear of ice until October 20. Solid ice cover was formed at Cape Hatt and Eclipse Sound by 27 October 1981, about three weeks later than in 1980. The Atmospheric Environment Service's seasonal break-up and thirty day forecasts were remarkably accurate in their 1981 ice predictions.

Time lapse film coverage of the Cape Hatt region was not as reliable as anticipated, with loss of coverage in Bays 102 and 103 due to camera malfunctions, no filming of break-up in Ragged Channel, and missing films of freeze-up (at time of writing). These difficulties may be attributed to the use of equipment already used for one season without factory checking or overhaul, and the fact that no one person was responsible for maintaining the stations in operation. Budget constraints also eliminated field observations of break-up and freeze-up from the monitoring pro gram.

6.0 RECOMMENDATIONS

The quality of the monitoring program could be improved through the use of new or reliably maintained camera equipment, and the delegation of one party responsible for camera station operations. Field observations when possible add considerable depth to coverage of freeze-up and break-up patterns and ice /shoreline interaction processes.

Studies of general ice conditions with the same network of time lapse stations, are not recommended for 1983. Instead, cameras should be deployed to study particular areas of interest such as the site of the neat oil spill in Bay 11, and to provide documentation of any ice mound study that may be conducted.

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ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of Peter Blackall and project staff who installed the 1981 camera stations and changed film during June and July; Robin Brown for preparing instructions and ensuring camera supplies on site; Ernie Reimer for his inspired tower design and erection; and Blair Humphrey for patiently waiting to film a freeze-up that never arrived.

APPENDIX A

Pond Inlet Ice Thickness Data (A. E.S. 1981)

Ice Forecast Summary, Northern Canadian Waters 1981

POND INLET, N.W.T.

OBSERVATION SITE: One mile north of Hudson Bay Co. Store.

DATE 1964	ICE THICKNESS (INCHES)	SNOW DEPTH (INCHES)	DATE 1965	ICE THICKNESS (INCHES)	SNOW DEPTH (INCHES)
Nov. 07	15.5		Apr. 03	54	6
Nov. 14	17		Apr. 10	55.5	6
Nov. 24	19.5		Apr. 17	56	6
Dec. 05	23		Apr. 24	57	6
Dec. 12	25		May 01	57	6
Dec. 19	26.5		May 08	58	6
Dec. .26	23		Pay 15	57	6
1965			May 22	56	6
Jan. 02	24.5		May 29	55.5	6
Jan. 12	25		June 05	-56	6
Jan. 16	36.5		June 12	57	6
Mar. 06	44.5	5.5	June 19	56	6
Mar. 13	47.5	6	June 26	52	6
Mar. 20	50	6	July 03	41	6
Mar. 27	52	6	July 10	35	
			July 17	29	

POND INLET, NWT

OBSERVATION SITE: 1 Mile north ofsecclemenc.

DATE 1968	ICE THICKNESS (inches)	SNOW DEPTH (inches)	DATE 1968	ICE THICKNESS (inches)	SNOW DEPTH (inches)
Nov. 15	4.0	01	Dec. 13	19.0	, 03
Nov. 22	6.0	03	Dec. 20	24.0	06
Nov. 29	9.0	06	Dec. 27	26.0	06
Dec. 06	15.0	02			

POND INLET, N.W.T.

OBSERVATION SITE: Une mile North of" Settlement

DATE 1968	ICE THICKNESS (inches)	SNOW DEPTH (inches)	DATE 1968	ICE THICKNESS (inches)	SNOW DEPTH _ ? = = | -
Mar. 15	37.0	07	May 24	55.0	10
Mar. 22	38.5	08	May 31	55.5	10
Mar. ,29	40.0	08	June 07	50.0	08
Apr. 05	41.5	08	June 14	47. o"	06
Apr. 12	43.0	09	June 21	46.0	04
Apr. 19	44.0	10	June 28	45.(	00
Apr. 26	49.5	09	July 05	37*5	00
May 03	51.0	09	July 12	34.0	00
May 10	51.0	10	July 19	30.0	00
May 17	53.0	10	July 26	24.0	00

POND INLET, N.W.T.

OBSERVATION SITE: 1 MILE NORTH OF HUDSON BAY COMPANY POST

DATE 1970	ICE THICKNESS (inches)	SNOW DEPTH (inches)	DATE 1970	ICE THICKNESS (inches)	SNOW DEPTH (inches)
Mar. 08	36.0	04	Apr. 17	44.0	11
Mar. 13	37.0	06	Apr. 24	44.0	10
Mar. 20	40.0	07	May 01	66.0	10
Mar. 27	40.5	06	May 08	46.0	08
Apr. 03	42.0	07	May 15	45.0	10
Apr. 10	44.0	07	May 22	46.0	10
			May 23	46.0	10

POND INLET, N.W.T.

OBSERVATION SITE: 800 metres offshore. 320 degrees from R.C. church.

DATE 1975	ICE THICKNESS (inches)	SNOW DEPTH (inches)	DATE 1976	ICE THICKNESS (inches)	SNOW DEPTH (inches)
Dec. 05	19.0	2	Jan. 02	32.0	7
Dec. 12	24.0	3	Jan. 09	36.0	6
Dec. 19	27.0	4	Jan. 16	40.0	3
Dec. 26	29.5	7	Jan. 23	41.0	7
Dec. 31	31.0	7	Jan. 30	41.5	7
			Jan. 31	42.0	7
			Feb. 06	46.5	8
			Feb. 13	47.0	6
			Feb. 20	53.0	5
			Feb. 27	57.0	5
			Feb. 28	59.0	4
			Mar. 04	57.5	4
			Mar. 11	58.0	4
			Mar. 18	63.0	6
			Mar. 25	64.0	4
			Mar. 31	65.0	4
			Apr. 02	66.5	5
			Apr. 09	68.5	5
			Apr. 16	68.5	5.5
			Apr. 23	67.0	4.5
			Apr. 30	74.0	7
			Hay 07	72.5	5.5
			May 14	76.0	5
			May 21	77.0	5
			May 28	76.0	5
			May 31	76.0	5

First permanent new ice:

Freeze over: 30 Nov. 1975

First breaks or deterioration: 18 June 1976

Water clear of ice: 29 August 1976

PONDINLET, IN. W.T.

OBSERVATION SITE: Eclipse Sound. 800 meters NW from Southerly Church.

Date 1974	Ice Thickness (inches)	Snow Depth (inches)	Date 1975	Ice Thickness (inches)	Snow Depth (inches)
Dec. 20	32.0	3	Jan. 03	33.0	3
Dec. 27	32.0	3	Jan. 10	42.0	3
Dec. 30	3s.0	3	Jan. 17	43.0	4
			Jan. 24	46.0	4
			Jan. 3 [	52.0	4
			Feb. 07	50.0	4
			Feb. 14	57.0	5
			Feb. ?1	59.0	5
			Feb. 28	61.0	5
			Mar. 07	60.5	5
			Mar. 14	64.5	5
			Mar. 2I	66.5	6
			Mar. 28	67.S	-6
			Apr. 04	69.0	6
			Apr. 18	70.0	6
			Apr. 25	70.0	8

POND INLET, N.W.T./T.N.-O.

MEASUREMENT SITE: 800 metres of fshore; northwest of H.B.C. store.
SITE DE MESURE: à 800 mètres de la rive, au nord-ouest du magasin de la compagnie de la Baie d' Hudson.

DATE 1977	ICE THICKNESS EPAISSEUR DE CA GLACE cm	SNOW THICKNESS EPAISSEUR DE LA NEIGE an
Nov. 05	17	02
11	27	04
18	32	05
25	32	04
Dec/ 02	53	03
Déc. 09	66	03
16	79	05
23	80	04
31	86	07

First permanent new ice/
Première glace nouvelle permanente:
21 October/octobre 1977.

To tal ice cover/
Couverture de glace totale:
21 October/octobre 1977.

First breaks or deterioration/
Premières fissures ou détérioration:
17 June/juin 1978.

DATE 1978	ICE THICKNESS EPAISSEUR DE LA GLACE cm	SNOW THICKNESS EPAISSEUR DE LA NEIGE an
Jan. 08	94	06
15	102	08
21	104	08
31	111	11
Feb/ 08	116	08
Fév. 14	118	10
19	117	10
28	118	10
Mar/ 07	124	10
Mars 12	108	10
23	138	11
29	141	17
Apr/ 04	145	14
Avr. 16	149	18
28	152	17
May/ 06	152	20
Mai 11	1s5	21
29	157	12
Jun/Juin 05	156	30

POND INLET, N.W.T./T.N.-O.

MEASUREMENT SITE: Approximately 600 metres offshore, west of R.C. Church.

SITE DE MESURE: à environ 600 mètres de la rive, à l'ouest de l'église Catholique.

DATE 1976	ICE THICKNESS EPAISSEUR DE LA GLACE cm	SNOW THICKNESS EPAISSEUR DE LA NEIGE cm	DATE 1977	ICE THICKNESS EPAISSEUR DE LA GLACE cm	SNOW THICKNESS EPAISSEUR DE LA NEIGE cm
Oct. 15	20	03	Jan. 07	108	19
27	32	03	14	111	22
29	32	0s	21	112	20
31	33	05	28	114	25
Nov. 05	42	10	Feb/ 04	119	23
12	42	09	Fév. 11	119	28
19	51	10			
26	62	05			
Dec/ 03	67	08			
Déc. 10	78	08			
17	81	09			
24	91	10			
31	93	18			

Date of/Date de: 1976

First permanent new ice/
Première glace nouvelle permanente:
07 October/octobre.

Total ice cover/
Couverture de glace totale:
22 October/octobre.

Date of/Date de: 1977

First breaks or deterioration/
Premières fissures ou détérioration:
15 June/juin.

Water clear of ice/
Eau libre de glace: 30 July/juillet.

POND INLET, N.W. T.

Measurement Site: Approximately 6 km northwest of R. C.M. P. building

Date 1981	Ice Thickness (cm)	Snow Thickness (cm)	Date 1981	Ice Thickness (cm)	Snow Thickness (cm)
Jan 30	76	9.2	May 08	149	N/A
Feb 06	86	6.2	May 15	148	N/A
Feb 13	86	6.0	May 23	147	N/A
Feb 23	107	3.0			
Feb 27	112	4.8	Nov 21	35	3.5
Mar 13	124	9	Nov 28	41	6.4
Mar 22	129	14	Dec 04	41	11.4
			Dec 11	45	14.0
Mar 27	134	13	Dee 18	m	m
			Dec 25	m	m

m = measurements missed due to bad weather

Ice Forecast Summary, Northern Canadian Waters 1981

The seasonal break-up pattern and outlook for northern Canadian waters, summer 1981, predicted ice fracture and clearing for Pond Inlet as follows:

	1980	Median	Outlook for 1981
Pond Inlet - fracture*	23 July	22 July	15-20 July
- clearing	13 Aug	18 Aug	10-15 Aug

*fracture indicates complete breakage of consolidated ice cover.

However Arctic temperatures averaged above normal during the first half of June 1981 and were expected to continue as such for the next thirty days. Lancaster Sound was nearly clear and open water conditions were found along the east end of Devon I sland joining the "Nort h Water" and Lancaster Sound. With these combined, the ice forecast issued for mid-June to mid-July 1981 predicted an advancement of about one week in the break-up pattern.

Reference: Atmospheric Environment Service

APPENDIX B

"Growth of First-Year Sea Ice, Eclipse Sound, Baffin Island, Canada"

by N .K. Sinha and M. Nakawo

National Research Council Canada
Conseil national de recherches Canada

GROWTH OF FIRST-YEAR SEA ICE, ECLIPSE SOUND, BAFFIN ISLAND, CANADA

by N. K. Sinha and M. Nakawo

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Growth of first-year sea ice, Eclipse Sound, Baffin Island, Canada

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A simple numerical integration method has been developed for predicting growth of ice under snow cover where solar radiation does not play a dominant role. The method is capable of incorporating variations in snow conditions and physical properties of ice and *snow* during [he growth period. Theoretical predictions compare favourably with field observations in Eclipse Sound, Baffin island, for the winter seasons *of* 1977-78 and 1978-79.

Une méthode simple d'integration numérique a été mise au point pour la prédiction de *la* croissance de la glace sous un champ de neige, clans les situations où le rôle du rayonnement solaire n'est pas determinant. Cette méthode permet de tenir compte des variations clans les conditions de la neige et des proprieties physiques de la glace et de la neige durant la période de croissance. Les observations qui ont été effectuées au *tours* des hivers 1977-78 et 1978-79 à Eclipse Sound, terre de Baffin, ont confirmé, clans une large mesure, les predictions théoriques.

CM. Geotech. J., 18, 17-23 (1981)

Introduction

Geotechnical activities in the north involving ice-covered water masses are on the increase. The safe use of floating ice sheets under static (e.g., drilling platform) and moving loads (e.g., ice bridges and air strips), the use of ice-breakers for moving through ice-covered waters, and the reaction of structures to a moving ice sheet are examples of engineering problems for which it is essential to know the thickness and temperature distribution. These are influenced by the past as well as the prevailing climatological conditions.

Several attempts have been made in the past to predict the growth of sea ice from climatological data (e.g., Zubov 1938, 1945; Tabata 1958; Billelo 1961; Assur and Weeks 1963; Michel 1972). These investigations have resulted in the development of successful empirical equations relating ice thickness to accumulated degreedays of frost. The empirical approach was taken mainly because necessary and reliable information on the growth conditions such as snow thickness and its properties, ice characteristics, data of freeze-up, etc. was lacking.

More recently, during the winters of 1977-78 and 1978-79, it has been possible to collect a large volume of data on weather, snow and ice characteristics, and temperature distribution in the ice at Eclipse Sound (72.7°N, 78.0°W) near Pond In[et, Baffin Island, Canada. These field data have permitted the development of a simple theory for predicting the growth of first-year sea ice. Ice thickness in the High Arctic can be predicted reasonably well if the daily mean temperatures, *snow* thickness, and its density are known.

Theory

Consider a growing ice sheet of thickness h_i with a *snow* cover of thickness h_s subjected to an ambient air temperature of T_a. If, for simplicity, the upper *snow* surface temperature is assumed to be the same as T_a, and if T_b *is* assumed to be the snow-ice interface temperature, then under steady-state conditions

$$[1]\quad G_i = (T_m - T_b)/h_i$$

and

$$[2]\quad G_s = (T_b - T_a)/h_s$$

where G_i and G_s are temperature gradients in ice and snow, respectively, and T_m is the melting point of sea ice. It is implicit in the assumption that the physical properties of ice and snow are uniform throughout their respective depths.

If the increase in thickness of the ice sheet is Δh_i in a time period Δt, then the quantity of heat released during freezing is $L\rho\Delta h_i$, where L is the latent heat of fusion and p the density of ice. This amount of heat must flow through the ice and *snow* to the atmosphere, assuming that there is no flow to the water underneath. Thus

$$[3]\quad L\rho\Delta h_i = k_i\left(\frac{T_m - T_b}{h_i}\right)\Delta t = k_s\left(\frac{T_b -}{h_s \quad ''}\right)^{A}\,'$$

0008-3674/8 1 /0100 17-07S01 .00/0

where k_i and k_s are the average thermal conductivities of ice and snow, respectively.

The second equality in [3] gives, after rearrangement,

$$[4] \quad T_b = \frac{k_i h_s T_m + k_s h_i T_a}{k_s h_i + k_i h_s}$$

Substitution of T_b from [4] in [1] and [2] gives, respectively,

$$[5] \quad G_i = \frac{T_m - T_a}{h_i + (k_i/k_s)h_s}$$

and

$$[6] \quad G_s = \frac{T_m - T_a}{(k_s/k_i)\, h_i + h_s}$$

Substitution of T_b from [4] in [3] and rearrangement gives

$$[7] \quad \Delta h_i = \frac{k_i k_s}{L\rho} \frac{T_m - T_a}{k_i h_s + k_s h_i} \Delta t$$

Suppose that $T_{a,N}$ is the mean air temperature of the Nth day from the date of freeze-up and Δt is a period of time equivalent to 1 day, that is $\Delta t = 1$. Equation [7] then gives a daily growth rate of

$$[8] \quad \Delta h_{i,N} = \frac{k_i k_s}{L\rho} \frac{(T_m - T_{a,N})}{(k_i h_{s,N} + k_s h_{i,N-1})}$$

where $h_{i,N-1}$ is the ice thickness at the end of $(N-1)$th day and $h_{s,N}$ is the average snow thickness on the Nth day.

The total ice thickness for a given day is then given by the sum of all the daily growth increments from the first freeze-up day to the day under consideration

$$[9] \quad \sum_1^N \Delta h_{i,N} = \sum_1^N \frac{k_i k_s}{L\rho} \frac{(T_m - T_{a,N})}{(k_i h_{s,N} + k_s h_{i,N-1})}$$

Equation [9] can be rearranged to give

$$[10] \quad \sum_1^N (T_m - T_{a,N}) = \sum_1^N \frac{L\rho}{k_i k_s} (k_i h_{s,N} + k_s h_{i,N-1})\, \Delta h_{i,N}$$

The left side of the above equation is the accumulated degree-days of freezing. Thus [10] describes growth of ice in terms of accumulated degree-days of freezing. The integral form of [10] is given by

$$[11] \quad \int_0^t (T_m - T_a)\, \mathrm{d}t = \int_0^{h_i} \frac{L\rho}{k_i k_s} (k_i h_s + k_s h_i)\, \mathrm{d}h_i$$

If the snow thickness is assumed to be constant, then [11] reduces to

$$[12] \quad \int_0^t (T_m - T_a)\, \mathrm{d}t = \frac{L\rho}{2k_i} h_i^2 + \frac{L\rho h_s}{k_s} h_i$$

which further reduces in the absence of snow cover to

$$[13] \quad \int_0^t (T_m - T_a)\, \mathrm{d}t = \frac{L\rho}{2k_i} h_i^2$$

Equation [12] bears close resemblance to Zubov's (1938) empirical formulation

$$[14] \quad \sum(T_m - T_a) = Ah_i^2 + Bh_i$$

where A and B are constants.

Equation [13], on the other hand, is similar to widely used empirical equations of the form

$$[15] \quad \sum(T_m - T_a) = Ch_i^D$$

applied successfully to field data by several investigators (for example, Tabata, 1958; Billelo, 1961). In [15] C and D are constants and D is usually found to be close to 2.

As this theory neglects the effect of incoming solar radiation, it should be applicable to the conditions of near absence of sunlight in the High Arctic during most of the season of ice growth and the low elevation of the sun during the rest of the period.

Methods of Field Observation

An observation area in the ice cover 100 m² was selected and marked each year at Eclipse Sound soon after the ice was safe. These areas were 0.5 km from the nearest shore where the main camp and laboratories of the Arctic Research Establishment were located, and the depth of water underneath was about 150 m. The selection was made during the first week of November for the 1977–78 season and towards the end of October for the 1978-79 season.

Ice cores were recovered from the chosen site at intervals of about a week during the first season and were recovered almost daily during the first 2 months of the second season. The coring locations were about 10 m apart to ensure undisturbed samples. Ice thickness and snow depth at the coring locations were recorded each time a core was removed. Each was taken to the main camp soon after recovery and sectioned into segments of 2.5 cm and then the salinity of each segment was measured by a standard method. Salinity profiles through the thickness of the ice sheet were thereby obtained as regularly as the cores were taken.

.%-tow density in the observation area was measured at regular intervals of about a week. This was accom-

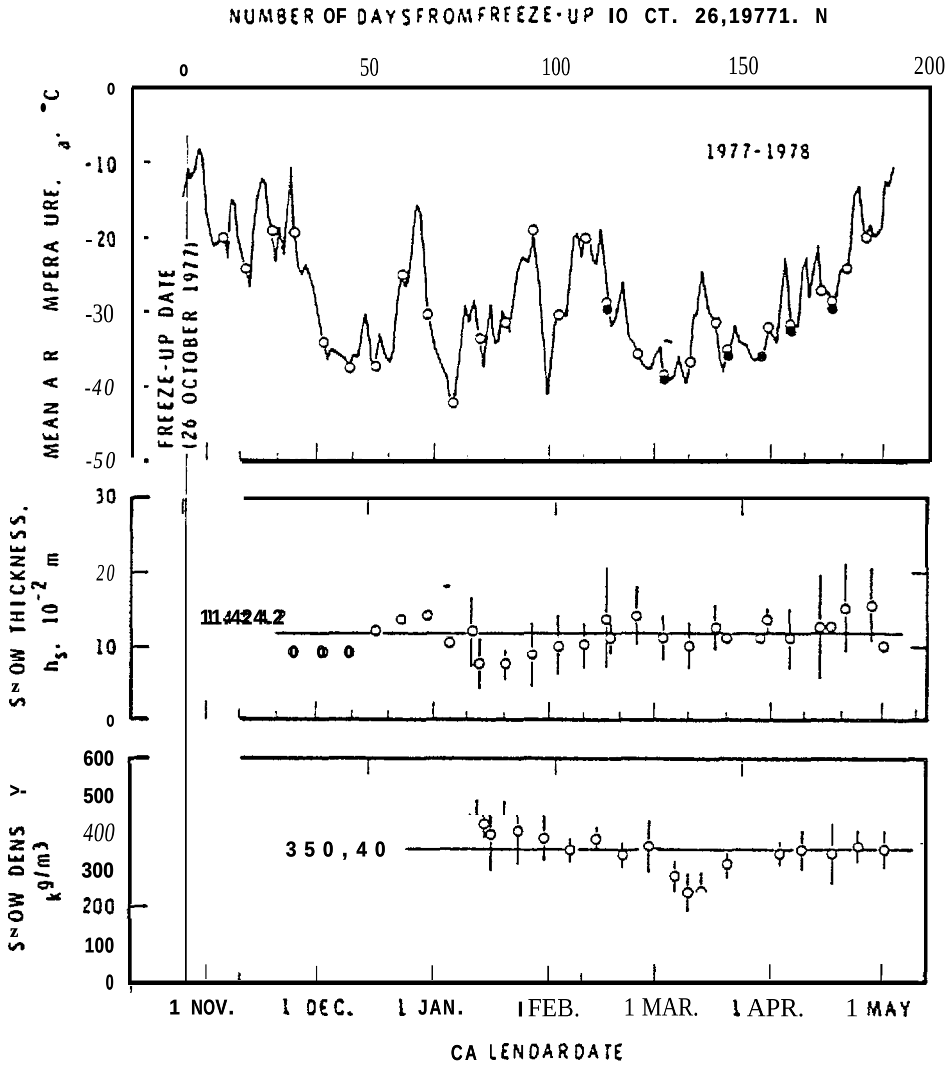

FIG. 1. Variation of daily mean air temperature, snow thickness, and snow density during the winter of 1977-78 at Pond Inlet. Open and solid circles in the recorded temperature variation indicate dates on which ice cores were taken and ice temperatures measured respectively. Single circles for snow thickness and density indicate single measurements, and circles with standard deviation bars describe the mean of about 6 measurements.

plished by taking snow cores of fixed diameter and known depth and determining their mass. During the latter part of each season six vertical snow cores were taken at a time (Figs. 1, 2), providing additional data on snow depth.

Daily maximum and minimum, and hence mean, air temperatures were recorded at the main camp for both the seasons under consideration. Temperature distribution through the ice thickness was also measured several times (Figs. 1, 2) by means of a 2 m long probe with waterproof thermocouple junctions placed 10 cm apart; the topmost sensor was placed in the ice only a few millimetres below the snow-ice interface.

General Field Results

Variations of daily mean air temperature for the major part of the two winter seasons are shown in Figs. 1 and 2, along with the recorded data on snow depth and density. Also shown are the dates on which ice cores were taken and ice temperatures measured. Figure 3 gives examples of measured ice temperatures.

Although the variation in snow depth did not suggest any specific pattern during the first season, the second was marked by a tendency towards gradual thickening of the snow cover. In general, the thickness of the snow cover varied widely not only with time but also with location. It was decided,

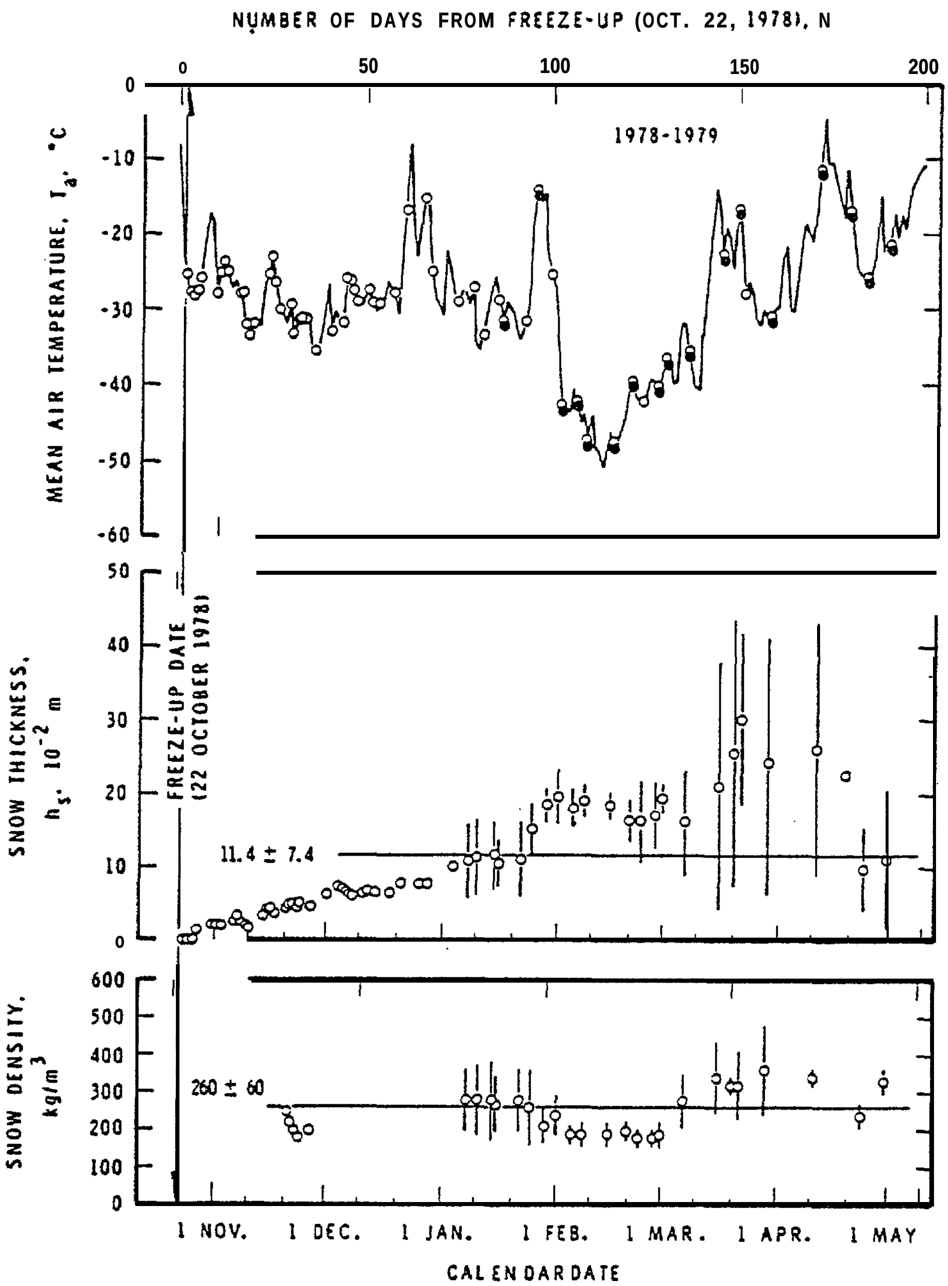

FIG. 2. Variation of daily mean air temperature, mow thickness, and snow density during the winter of 1978-79 at Pond Inlet. Open and solid circles in the recorded temperature variation indicate dates on which ice cores were taken and ice temperatures measured *respectively*. Single circles for snow thickness and density indicate single measurements, and circles with standard deviation bars give the mean value of about 6 measurements.

therefore, to estimate an average annual snow thickness for both seasons in order to represent the general snow condition in the test area. Average snow depth for 1977-78 was 11.4 ± 4.2 cm; for 1978-79 it showed the same value as for the previous year with a different scatter (11.4 ± 7.4 em).

The average seasonal snow density was 350 ± 40 kg m^{-3} in 1977-78 (Fig. 1) and 260 ± 60 kg m^{-3} in 1978-79 (Fig. 2). The first measurement agreed with an earlier survey by Williams and Gold (1958) of 356 ± 52 kg m^{-3} at Resolute Bay, about 400 km from Pond Inlet, whereas the second differed significantly.

In agreement with innumerable previous observa-

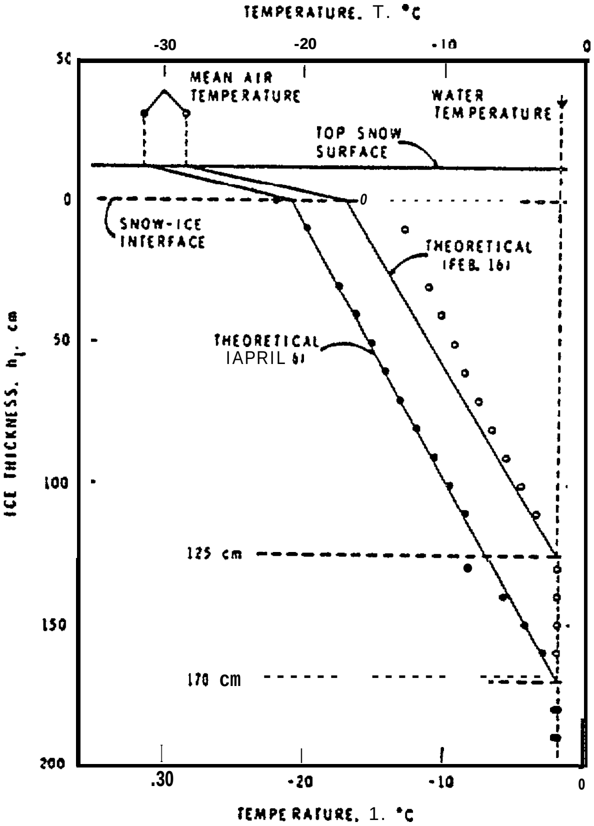

FIG. 3. Comparison of *measured* and theoretical temperature distributions in the ice sheet for 2 days in 1978.

TABLE 1. Physical properties of snow and ice

Average salinity of water in the test area in Eclipse Sound = 32‰	
T_m	= −1.8°C for sea water with salinity of 32‰ (see *also the* measured water temperature in Fig. 3)
ρ	= 900 ± 10 kg m^{-3} (density of sea ice at Eclipse Sound, measured at DBR/NRC)
L	= 70 cal g^{-1} (293 J g^{-1}) (Anderson 1960; Schwerdtfeger 1963; Ono 1968)
k_i	= 5 × 10^{-3} cal cm^{-1} s^{-1} °C^{-1} (2.1 W m^{-1} °C^{-1}) for sea ice of about 6‰ salinity (Schwerdtfeger 1963; Ono 1968)
h_s	= 11.4 ± 4.2 cm (average snow thickness for 1977-78)
	= 11.4 ± 7.4 cm (average *snow thickness* for 1978-79)
Snow density	= 350 ± 40 kg m^{-3} (average value for 1977–78)
	= 260 ± 60 kg m^{-3} (average value for 1978-79)
k_s	= 6 × 10^{-4} cal cm^{-1} s^{-1} °C^{-1} (0.25 W m^{-1} °C^{-1}) for snow density of 350 kg m^{-3} at -20 to −30°C (Pitman and Zuckerman 1967; Mellor 1977)
	= 4 × 10^{-4} cal cm^{-1} s^{-1} °C^{-1} (0.17 W m^{-1} °C^{-1}) for snow density of 260 kg m^{-3} at -20 to −30°C (Pitman and Zuckerman 1967; Mellor 1977)

tions on first-year sea ice, salinity was observed to be high at the top as well as at the bottom of almost all the ice cores. The average bulk salinity of the ice was high during the early growth period in October–November, but decreased to a quasi-stable bulk value of about 6‰ from December on. Evolution of the salinity profile in the ice during 1977-78 is shown in Fig. 4, in which the vertical solid lines at a value of 6‰ are given as a reference. Similar observations were made in 1978-79. It is perhaps important here to mention that the distribution of salinity through the thickness has been shown to be related to previous climatological conditions (Nakawo and Sinha 1981).

Analysis

Theoretical analysis, given earlier, was simplified by assuming steady-state heat flow *or,* in other words, linear temperature distributions in both the snow

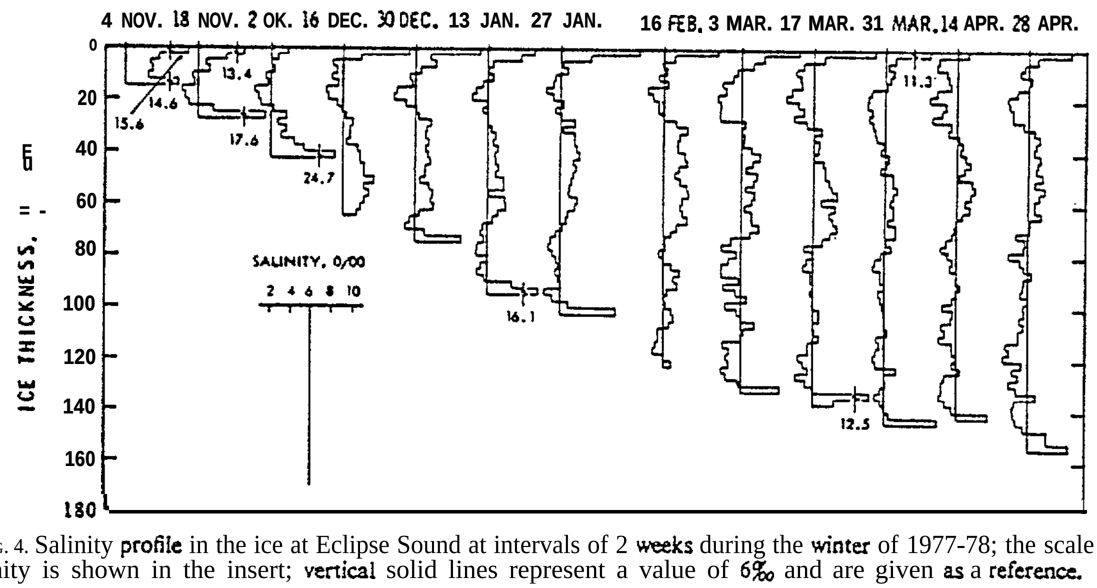

FIG. 4. Salinity profile in the ice at Eclipse Sound at intervals of 2 weeks during the winter of 1977-78; the scale for salinity is shown in the insert; vertical solid lines represent a value of 6‰ and are given as a reference.

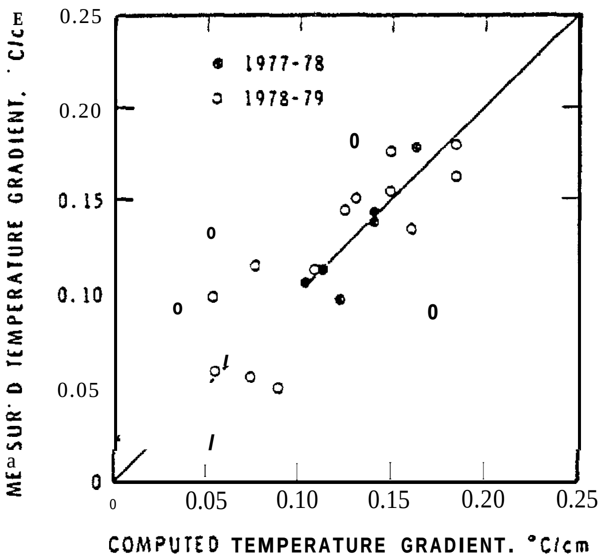

FIG. 5. Comparison of calculated and measured temperature gradients in the ice sheet for 6 measurements carried out February-Aprii 1978 and 17 measurements carried out January-April 1979 at Eclipse Sound.

cover and the ice sheet below the *snow*. There was a need, therefore, to examine the applicability of this basic assumption using the field data.

Computed temperatures of the snow-ice interface and the temperature distributions in the snow and ice are compared with measured data in Fig. 3. Calculations were made, using the illustrated ice thicknesses estimated from the observed temperature distributions, snow thickness of 11.4 cm, and the material properties relevant to the observed snow and ice conditions (Table 1). Theoretical prediction for 16 February 1978 (Fig. 3) indicates that some consideration should be given to the thermal history previous to the days of measurement because the warm week prior to 16 February (see Fig. 1) led to a warmer ice sheet than that predicted.

A complete analysis must take into consideration the effects of wind and cloud cover, if any, on the heat transfer conditions at the exposed snow surface, the disturbance that might be introduced in temperature distribution by the presence of the probe, and the uncertainty of the thermal conductivities of snow arid the highly saline upper and bottom layers of the ice, etc. These refinements are necessary for short-terrn comparisons of theoretical and measured quantities. The general agreement between estimated and measured temperature gradients in the ice (Fig. 5) supports reasonably well the validity of the assumptions over a long period. Figure 5 presents 6 tempera-

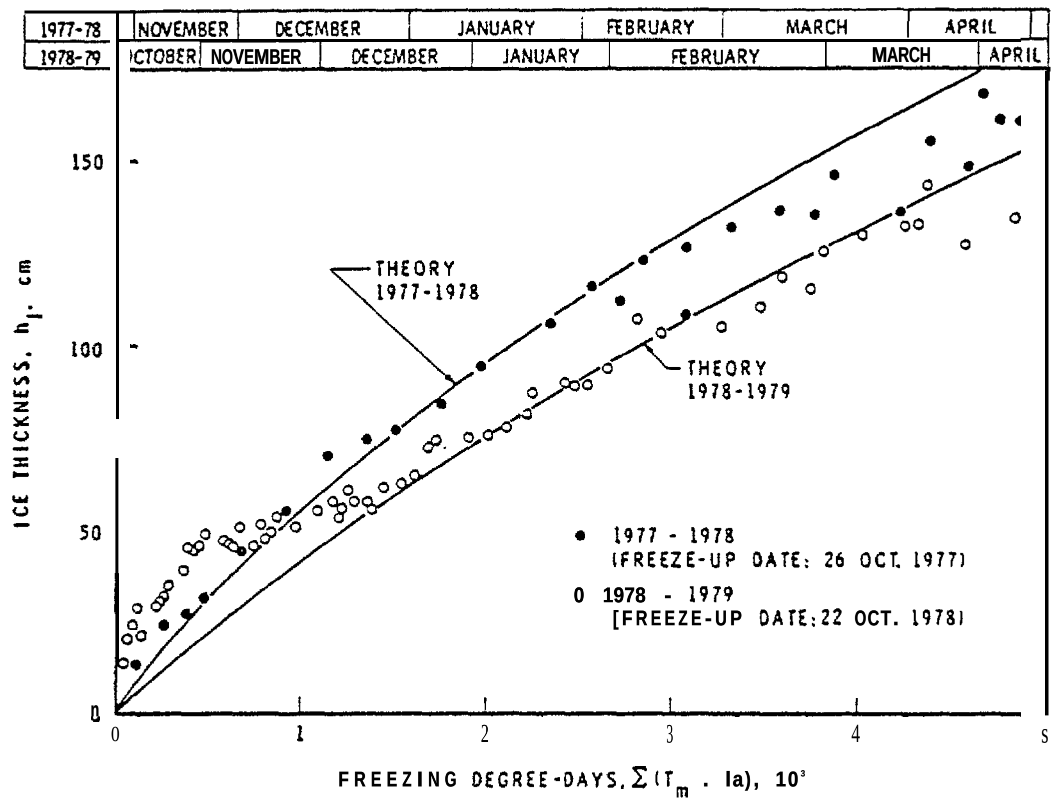

FIG. 6. Growth of the ice at Eclipse Sound during the winters of 1977-78 and 1978-79.

ture measurements from the first season (Fig. 1) and 17 measurements from the second season (Fig. 2). In all these calculations a constant snow cover of 11.4 cm was used with, however, different k_s values to take account of differences in *snow* densities from one year to another, as given in Table 1.

Growth of ice in the test areas at Eclipse Sound during the two seasons under consideration are shown in Fig. 6 as a function of accumulated degree-days of freezing. Dates given at the top of the figure indicate the time of *the* season. Calculated results. based on [10] and constant snow thickness of 11.4 cm and appropriate k_s values, agree reasonably well with the observations.

The theory underestimates ice thickness during the early part of the season and overestimates it towards the end. The use of measured **snow** thickness in calculating the temperature gradient in the ice on any given day and, correspondingly, the use of variable snow thickness (particularly for 1978-79) in computing ice growth might seem to give better agreement with the measurements. Calculations were therefore made using the observed snow thickness variation. These gave better agreement with observations during the early growth period, but did not provide better comparison as a whole. The overall success of calculations using constant *snow cover* lies in the possibility that assumed thicker *snow* somehow compensates for the effect of the low k_i and k_s of thinner snow cover during the early stage. The late season deviation in March or thereafter was most probably caused by increasing solar radiation.

Conclusion

The temperature distribution through a sea-ice sheet at Eclipse Sound near Pond Inlet in the High Arctic was approximately linear during most of the winters of 1977-78 and 1978-79 when observations were made. Temperature gradient, however, was dependent on existing ‘air temperature. This dependency is now shown to be predictable with a simple theory, provided that the thickness of ice and snow cover are known and that information on their density and the salinity of the ice are also known. It is shown, further, that *a* simple theoretical prediction of growth rate and thickness can be reasonably reliable for first-year sea ice for growth conditions under which solar radiation is not a major component of the heat flux. Sufficient data on snow depth and density and a record of daily air temperatures are essential for these calculations.

Acknowledgments

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